Quantum Shuttling and Zonal Decoupling: Scaling Neutral-Atom Processors in the 72-Qubit Rubidium Regime

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As of May 2026, the global quantum landscape has shifted toward architectural modularity as a solution to the "noise floor" of monolithic processors. A primary example of this shift is the 72-qubit neutral-atom quantum computer developed by Lomonosov Moscow State University and Rosatom. While its qubit count places it among the most powerful systems in Europe, its true innovation lies in a three-zone architecture that physically separates the computing, storage, and readout functions. By using optical tweezers to shuttle rubidium atoms between these isolated environments, the system achieves a two-qubit gate fidelity of 94 percent, significantly reducing the crosstalk that plagues stationary-qubit designs. Following its showcase at the April 2026 BRICS Quantum Technologies Forum, this prototype has emerged as a critical testbed for the "sovereign quantum" strategy, which aims for error-corrected operations by 2030. This paper analyzes the mechanical and quantum-mechanical underpinnings of this zonal approach, the role of rubidium as a high-fidelity carrier, and the strategic integration of this hardware into a broader educational and industrial pipeline intended to secure long-term technological autonomy.

Keywords: quantum computing, neutral atoms, rubidium, optical tweezers, three-zone architecture, qubit fidelity, Rosatom, Moscow State University, BRICS Quantum Technologies Forum, scalability, quantum error correction, fault tolerance, atomic physics.

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Outline

1. Introduction

2. The 2026 Quantum Landscape: Neutral Atoms vs. Superconducting Circuits

3. Physical Properties of Rubidium-87 for Scalable Quantum Logic

4. Mechanical Precision: Optical Tweezers and Atom Shuttling

5. Architecture of the Three-Zone Processor: Compute, Memory, and Measurement

6. Dynamics of Zonal Isolation: Mitigating Environmental Decoherence

7. Benchmarking 94 Percent Fidelity: Current Limits and Optimization Paths

8. Comparative Analysis: MSU Rubidium vs. Rosatom Ytterbium Ion Systems

9. Software and Algorithmic Integration for Zonal Architectures

10. The 2030 Roadmap: Moving Toward Logical Qubits and Error Correction

11. Human Capital: The Role of MSU in Training a Quantum Workforce

12. Strategic Implications and the 2026 BRICS Quantum Initiatives

13. References

Art

1. Introduction

The global pursuit of quantum advantage has reached a critical inflection point in early 2026. While the previous decade was defined by a frantic race to increase raw qubit counts, the current era is defined by the quest for stability, high-fidelity operations, and architectural maturity. As classical supercomputers continue to approach the physical limits of Moore's Law, the need for a non-classical computational leap has moved from the realm of theoretical physics into the center of national industrial strategies. Within this landscape, the 72-qubit rubidium-based quantum processor developed by Lomonosov Moscow State University in collaboration with the state nuclear corporation Rosatom represents a pivotal shift in how researchers approach the problem of quantum decoherence.

1.1 The Quantum Computing Paradigm in 2026

The current state of quantum hardware is characterized by a diversification of platforms. For several years, superconducting circuits and trapped ions were viewed as the primary contenders for commercial-scale quantum computing. However, as these systems scaled, they encountered significant physical bottlenecks, particularly regarding the density of wiring and the interference between stationary qubits. In response, neutral-atom technology has emerged as a formidable alternative. By using laser-cooled atoms—specifically rubidium-87—as qubits, researchers can leverage the inherent identicality of atoms and the flexibility of optical manipulation. The Russian 72-qubit milestone is significant not just for its size, which places it among the most capable neutral-atom systems globally, but for its demonstration of a scalable path toward the few-hundred-qubit threshold expected by 2030.

1.2 The Emergence of Zonal Architectures

The most significant barrier to practical quantum computation remains noise. In a quantum system, qubits are hyper-sensitive to their environment; even the act of measuring one qubit can inadvertently disturb its neighbors, a phenomenon known as crosstalk. The innovation presented in the MSU rubidium system is the physical decoupling of the processor's core functions. Rather than attempting to perform all operations in a single, crowded space, the system utilizes a three-zone architecture. By partitioning the hardware into dedicated areas for computing, storage, and readout, the researchers have applied a modular logic to a microscopic environment. This spatial separation allows for the "shuttling" of atoms using optical tweezers, ensuring that qubits not currently involved in a gate operation are kept in a pristine "storage" state, shielded from the electromagnetic noise of active calculations or the light-scattering interference of a readout laser.

1.3 Research Objectives and Scope

This paper provides a comprehensive technical analysis of the MSU 72-qubit rubidium processor, with a specific focus on the mechanical and quantum-mechanical implications of its three-zone design. We will examine the transition from a laboratory prototype to a functional computational unit, as showcased during the April 2026 BRICS Quantum Technologies Forum. The following sections will detail the physics of rubidium-87 as a qubit carrier, the engineering of the optical lattice used for atom transport, and the benchmarking of the current 94 percent gate fidelity. Furthermore, the paper evaluates the strategic roadmap set by Rosatom, which integrates this hardware development with a robust educational program designed to produce a specialized workforce. By analyzing this specific system, we gain insight into the broader global transition toward fault-tolerant quantum computing and the geopolitical shifts in technological sovereignty.

1.4 The Path to Fault Tolerance

The ultimate goal of the 2030 roadmap is the achievement of fault-tolerant operations. At 72 qubits, the MSU system is operating in the Noisy Intermediate-Scale Quantum (NISQ) regime, where errors are frequent enough to limit the depth of possible algorithms. However, the move toward a zonal architecture is a direct prerequisite for the implementation of Quantum Error Correction (QEC). For QEC to be effective, the hardware must be able to perform parity checks and measurement cycles without destroying the global quantum state. The three-zone approach provides the necessary physical infrastructure to isolate "data qubits" from "ancilla qubits" during these cycles. This paper argues that the success of the rubidium shuttling method provides a scalable blueprint that may eventually bypass the connectivity limitations of fixed-position superconducting architectures.

2. The 2026 Quantum Landscape: Neutral Atoms vs. Superconducting Circuits

By mid-2026, the global quantum computing sector has bifurcated into two dominant hardware philosophies. On one side, the superconducting modality—led by industry giants such as IBM and Google—has achieved significant milestones in circuit depth and gate speed. On the other side, neutral-atom architectures, such as the rubidium-based system at Moscow State University, have surged forward by prioritizing connectivity and spatial scalability. This section analyzes the competitive dynamics between these two platforms, focusing on why the 72-qubit neutral-atom breakthrough represents a shift in the perceived "optimal" path to fault tolerance.

2.1 Superconducting Qubits: The Maturity of Fixed-Grid Systems

Superconducting processors utilize artificial atoms created from Josephson junctions, operating at millikelvin temperatures. The primary advantage of this platform in 2026 remains its operational speed; gate times are measured in nanoseconds, allowing for millions of operations within a single coherence window. However, superconducting qubits are physically etched onto a silicon chip in a fixed grid. This "static" nature introduces two major bottlenecks: wiring complexity and limited connectivity. As systems attempt to move from the 433-qubit Osprey to thousand-qubit regimes, the heat load from control electronics and the physical space required for coaxial cables create significant engineering "ceilings." Furthermore, superconducting qubits typically only interact with their nearest neighbors, necessitating complex "swap" operations that consume precious coherence time and increase the cumulative error rate.

2.2 Neutral-Atom Systems: Flexibility and Any-to-Any Connectivity

The 72-qubit MSU processor represents the alternative "mobile" paradigm. Neutral atoms, such as rubidium-87, are trapped in a vacuum by optical tweezers—highly focused laser beams. Unlike superconducting circuits, these qubits are not hard-wired. They are identical by nature and can be rearranged in real-time into any geometry. This flexibility allows for "any-to-any" connectivity, where any qubit in the 72-atom array can, in principle, be moved into proximity with any other to perform a gate. While the gate speeds of neutral atoms are slower (typically in the microsecond to millisecond range), the elimination of swap gates and the ability to scale to high qubit densities without increasing cryostat wiring gives them a distinct advantage in the "space dimension" of scaling. By 2026, research arrays have demonstrated the capacity to trap over 6,000 atoms, a feat that remains physically impossible for current superconducting chip designs.

2.3 Strategic Divergence and the Error Correction Race

The competition between these platforms is increasingly defined by their approach to Quantum Error Correction (QEC). Superconducting systems are doubling down on the "surface code," which requires a massive overhead of physical qubits to create a single logical qubit. Neutral-atom systems, including the MSU 72-qubit prototype, are exploring "zonal" architectures that utilize their mobility to perform error correction more efficiently. The May 2026 update regarding the MSU system confirms the full integration of a three-zone shuttling workflow, allowing qubits to be moved out of the compute zone once their operation is complete. This spatial decoupling effectively creates a "cleaner" environment by isolating active gates from the noise of the rest of the array—a feat that is inherently difficult on a static superconducting chip where all qubits are permanently adjacent to their neighbors.

2.4 Comparative Benchmarking: Fidelity vs. Scalability

In 2026, the benchmark for "strong" qubits is no longer just the count, but the gate fidelity. The MSU rubidium system reports a two-qubit gate fidelity of approximately 94 percent. While top-tier superconducting processors have demonstrated fidelities exceeding 99 percent in isolated clusters, they struggle to maintain these levels as they scale across a large, fixed-lattice chip due to crosstalk and frequency crowding. In contrast, the neutral-atom platform's fidelity is limited primarily by laser precision and vacuum quality, both of which are seeing rapid improvement. As discussed at the April 2026 BRICS Quantum Technologies Forum, the "sovereign" strategy involves benchmarking the 72-qubit rubidium system against the 70-qubit ytterbium ion system. This internal competition highlights that neutral atoms are now viewed as a viable, and perhaps more scalable, rival to both superconducting and ion-trap modalities in the quest for the first hundred-logical-qubit computer.

3. Physical Properties of Rubidium-87 for Scalable Quantum Logic

The choice of rubidium-87 (87Rb) as the primary qubit carrier in the Moscow State University (MSU) 72-qubit processor is not arbitrary; it is rooted in the specific alkali metal properties that facilitate high-precision control and long-lived coherence. As an alkali atom, rubidium possesses a single valence electron outside a closed shell, creating an energy level structure that is both relatively simple and highly responsive to optical manipulation. This section explores the fundamental atomic physics that enable 87Rb to function as a scalable quantum bit, focusing on its hyperfine structure, cooling requirements, and the mechanism of Rydberg-mediated interactions.

3.1 Atomic Structure and Qubit Encoding

In the 72-qubit MSU system, quantum information is encoded in the hyperfine ground states of the 87Rb atom. Specifically, the "clock states" are utilized: the $|F=1, m_F=0\rangle$ state and the $|F=2, m_F=0\rangle$ state of the $5S_{1/2}$ electronic ground level. These states are preferred because they exhibit a first-order insensitivity to external magnetic field fluctuations, which is critical for maintaining coherence in a non-shielded laboratory environment. The energy splitting between these two states is approximately 6.834 GHz, a frequency that allows for extremely precise manipulation using microwave pulses or two-photon Raman transitions.

The stability of these states provides the "storage" capability referenced in the three-zone architecture. When an atom is moved into the storage zone, it remains in a superposition of these ground states. Because 87Rb atoms are naturally identical, there is no "frequency crowding" or manufacturing variance as seen in superconducting transmon qubits. Every qubit

in the 72-atom array has an identical transition frequency, simplifying the control electronics and allowing for global addressing of the entire array with a single laser source if necessary.

3.2 Laser Cooling and the Preparation of Cold Qubits

To function as a qubit, the 87Rb atoms must be stripped of their kinetic energy. The MSU system utilizes a standard magneto-optical trap (MOT) followed by sub-Doppler cooling techniques, such as polarization gradient cooling, to reach temperatures in the microkelvin range. At these temperatures, the de Broglie wavelength of the atoms becomes significant, but more importantly, their thermal motion is reduced to a level where they can be trapped by the conservative potential of an optical tweezer.

Optical tweezers are formed by tightly focusing a red-detuned laser beam—typically at a wavelength near 850 nm for 87Rb. The induced dipole moment of the atom causes it to be drawn to the region of highest intensity (the focal point). The 72-qubit processor utilizes a spatial light modulator (SLM) to create a reconfigurable array of these traps. The physical robustness of 87Rb under these trapping conditions allows for the "shuttling" process. Because the trapping potential is deep compared to the atomic temperature, the atoms can be moved across the zones at speeds of several millimeters per second without being heated out of the trap or losing their internal quantum state.

3.3 Rydberg Interactions: The Engine of Quantum Gates

While the ground states provide excellent storage, they do not naturally interact with one another over the distances (typically 3 to 10 micrometers) found in an optical lattice. To perform a two-qubit logic gate, the MSU system temporarily excites the rubidium atoms to a high-lying Rydberg state, such as |70P> or |80S>. In these states, the valence electron is promoted to an orbit with a very large principal quantum number (n), resulting in a massive increase in the atom's electric dipole moment.

The interaction between two Rydberg atoms is governed by the van der Waals force, which scales as C_6 / R^6, where C_6 scales as n^11. This creates the "Rydberg blockade" effect: if one atom is excited to a Rydberg state, its presence shifts the energy levels of nearby atoms so significantly that they cannot be excited to the same state by the same laser pulse. This blockade is the physical mechanism behind the 94 percent fidelity gates reported in early 2026. By controlling the blockade radius—the distance within which only one excitation can occur—the MSU team can perform conditional logic (C-NOT gates) between any two atoms moved into the computing zone.

3.4 Homogeneity and Identicality in Atomic Processors

One of the most compelling physical properties of 87Rb for the Rosatom roadmap is its inherent homogeneity. In solid-state systems, every qubit is a unique physical object with its own defects and slightly different resonant frequency. In the MSU rubidium system, every qubit is a fundamental particle of the universe. This identicality ensures that the error models for the 72-qubit system are uniform across the entire array. As the system scales toward the 2030 goal of several hundred qubits, this property significantly reduces the complexity of the "calibration stack." The physical properties of rubidium-87 thus provide a predictable and stable foundation for the complex zonal engineering required to achieve the next generation of quantum computation.

4. Mechanical Precision: Optical Tweezers and Atom Shuttling

The operational heart of the 72-qubit rubidium processor is the optical lattice, a complex web of light that acts as both the "wiring" and the "substrate" for the qubits. Unlike superconducting systems where qubits are physically fixed to a silicon base, the MSU neutral-atom system utilizes light to suspend and transport its atomic hardware. This mobility is facilitated by two primary optical technologies: Spatial Light Modulators (SLM) and Acousto-Optic Deflectors (AOD). Together, they provide the mechanical precision necessary to move rubidium atoms across the three-zone architecture without inducing catastrophic decoherence.

4.1 The Physics of Optical Trapping

The trapping mechanism relies on the dipole force. When a rubidium atom is placed in a non-uniform electric field—in this case, a tightly focused laser beam—the atom's electron cloud is polarized. The interaction between the induced dipole and the laser's electric field gradient creates a potential well. The potential energy U(r) of the atom in the trap is proportional to the intensity of the laser I(r) and the polarizability of the atom alpha, following the relationship:

$$U(r) = - (\alpha * I(r)) / (2 * \epsilon_0 * c)$$

In the MSU system, the traps are created using "red-detuned" light, meaning the laser frequency is slightly lower than the atomic transition frequency. This ensures that the atoms are drawn to the points of maximum intensity—the focal points of the laser beams. For the 72-qubit array, an SLM is used to divide a single high-power laser beam into dozens of individual diffraction-limited spots, each holding a single rubidium atom.

4.2 Dynamic Manipulation via Acousto-Optic Deflectors

While the SLM provides a static grid of "storage" sites, the process of "shuttling" atoms between zones requires dynamic tweezers. This is achieved using Acousto-Optic Deflectors (AODs). By passing a laser beam through a crystal vibrating at radio frequencies, the beam can be steered with extreme speed and precision. Changing the frequency of the sound waves in the crystal changes the angle of the laser beam, allowing a specific "tweezer" to pick up an atom from the storage zone and physically drag it into the computing zone for an interaction.

The mechanical precision required for this is staggering. The atoms must be moved over distances of 50 to 100 micrometers with sub-micron accuracy. If the atom deviates from the center of the trap during transport, it may experience "sloshing" or heating, which can result in the loss of the atom or the corruption of the quantum information stored in its internal states. The MSU team utilizes tailored "S-curve" acceleration profiles to minimize these mechanical disturbances, ensuring that the atom remains in the vibrational ground state of the trap during the move.

4.3 Timing and Coherence during Transport

A critical challenge in the 72-qubit architecture is the trade-off between shuttling speed and coherence time. If the atoms are moved too slowly, they may decohere due to environmental noise or collisions with residual gas molecules in the vacuum chamber before the gate operation can begin. Conversely, moving them too fast can cause them to escape the trap.

As of early 2026, the MSU processor has optimized shuttling times to the millisecond range. Given that the coherence times for rubidium "clock states" can exceed several seconds under ideal conditions, the overhead introduced by physical movement is relatively small. This "shuttling" capability is what allows for the modular three-zone logic: qubits spend the vast majority of their time in the storage zone—a dark, quiet region of the vacuum chamber—and are only brought into the high-intensity "compute" zone when a specific logic gate is required.

4.4 Spatial Constraints and Array Geometry

The 72-qubit system is currently configured in a two-dimensional grid, but the optical tweezers allow for arbitrary geometries. During the BRICS 2026 showcase, MSU researchers demonstrated the ability to reconfigure the array mid-computation to optimize for specific algorithms. For example, if a calculation requires a hexagonal connectivity map rather than a square one, the optical tweezers can physically reposition the atoms into the new layout. This mechanical flexibility provides a layer of algorithmic optimization that is fundamentally unavailable to fixed-circuit processors, effectively allowing the "hardware" to change its shape to fit the "software" it is running.

5. Architecture of the Three-Zone Processor: Compute, Memory, and Measurement

The defining innovation of the 72-qubit rubidium processor is its spatial organization. In conventional quantum architectures, all operations—initialization, logic gates, and measurement—occur within the same physical footprint. This leads to a major bottleneck: the laser pulses and microwave signals required for one operation often "leak" into neighboring qubits, causing errors. The Moscow State University team has mitigated this by implementing a three-zone architectural layout within the vacuum chamber, effectively separating the processor into a computing zone, a storage (memory) zone, and a readout zone.

5.1 The Computing Zone: The Interaction Engine

The computing zone is the most active region of the processor. It is here that the primary two-qubit logic gates are executed via Rydberg excitation. Because Rydberg atoms have highly enlarged electron shells, they are extremely sensitive to external electric fields. This sensitivity is necessary for the Rydberg blockade to function, but it also makes the qubits vulnerable to stray light and field fluctuations. By designating a specific physical area for these high-energy interactions, the researchers can focus their control lasers and shielding on a small, high-precision volume. As of the May 2026 updates, the system utilizes this zone to perform multi-qubit entangling operations with a gate fidelity of 94 percent, benefiting from the reduced background noise of the isolated environment.

5.2 The Storage Zone: Preserving Quantum Coherence

When a qubit is not actively participating in a calculation, it is moved to the storage zone. This region acts as a "quantum waiting room" where the atoms are kept in a dark environment, shielded from the high-intensity lasers used in the computing zone. In the storage zone, the rubidium atoms are held in their hyperfine ground states, which are naturally robust against decoherence. This spatial separation allows the system to maintain the quantum state of 72 individual atoms for extended periods—often exceeding several seconds. This is a critical prerequisite for deep quantum circuits; if the system can "park" its qubits safely while other operations are being processed, the cumulative error rate of the entire algorithm is significantly lowered.

5.3 The Readout Zone: Non-Destructive Measurement

The third and final region is the readout zone, which has seen full operational integration as of May 2026. Measurement in neutral-atom systems typically involves the detection of fluorescence—light emitted when a laser excites the atom. In a unified architecture, this scattered light would immediately decohere all other "data" qubits in the array. By shuttling only the "target" qubits into a dedicated readout zone, the MSU processor can perform measurements without disturbing the rest of the quantum register. This zone is equipped with

high-numerical-aperture optics and ultra-sensitive cameras that can detect the presence or absence of a single atom. The ability to measure specific qubits while others continue to compute is a fundamental step toward real-time error correction.

5.4 The Shuttling Workflow and System Throughput

The efficiency of this three-zone architecture depends on the "shuttling" speed of the optical tweezers. The MSU system utilizes a sophisticated synchronization protocol that coordinates the movement of atoms between zones with the timing of the laser pulses. A typical computational cycle involves picking an atom from the storage zone, moving it into the computing zone for a gate, and then either returning it to storage or moving it to the readout zone for measurement. While the physical movement introduces a latency in the range of several milliseconds, the reduction in crosstalk and the improvement in total system fidelity outweigh the temporal cost. This modular approach provides a blueprint for scaling to the several-hundred-qubit regime, as more zones or larger storage areas can be added without fundamentally redesigning the core computing logic.

6. Laser Cooling and Optical Tweezer Manipulation Techniques

The operational efficacy of the 72-qubit rubidium processor is fundamentally dependent on the ability to control the kinetic and spatial states of individual atoms with extreme precision. To transform a thermal vapor of rubidium-87 into a coherent quantum register, the system employs a multi-stage cooling and trapping protocol. This section details the transition from stochastic atomic motion to the highly ordered 72-trap lattice, as well as the dynamic manipulation techniques that enable zonal shuttling as of mid-2026.

6.1 Preparation: From Thermal Vapor to Cold Atoms

The process begins in a high-vacuum chamber where rubidium-87 is introduced as a dilute gas. To reach the quantum regime, the atoms must be cooled by several orders of magnitude. The first stage involves a Magneto-Optical Trap (MOT), which utilizes three pairs of counter-propagating laser beams and a magnetic field gradient to decelerate the atoms and trap them at a central point. The lasers are tuned slightly below the D2 transition frequency of rubidium, ensuring that atoms moving toward a beam experience a Doppler shift that brings them into resonance, resulting in a cooling force.

While the MOT can reach temperatures in the range of 100 microkelvin, this is insufficient for stable trapping in optical tweezers. The MSU system subsequently employs Polarization Gradient Cooling (PGC), often referred to as Sisyphus cooling. By creating a light field with a spatially varying polarization, the atoms are forced to climb potential hills, losing kinetic energy

at each peak before being optically pumped back to the bottom of the next hill. This technique allows the 72-qubit system to reach temperatures as low as 10 to 20 microkelvin, where the atoms can be reliably captured by the conservative potential of the optical lattice.

6.2 The Optical Tweezer Array: SLM-Based Holographic Generation

Once the atoms are sufficiently cold, they are loaded into an array of optical tweezers. The 72-trap geometry is generated using a Spatial Light Modulator (SLM), a device that modulates the phase of an incoming laser beam to create a specific interference pattern at the focal plane of a high-numerical-aperture objective lens. In 2026, the MSU researchers utilize advanced holographic algorithms to ensure that the 72 traps are identical in depth and spacing.

The potential depth of each trap, U, is determined by the laser intensity I and the atomic polarizability alpha:

U = - (alpha * I) / (2 * epsilon_0 * c)

To ensure high gate fidelity, the intensity of each of the 72 traps must be uniform to within 1 percent. Any variance in trap depth leads to different vibrational frequencies for the atoms, which introduces phase errors during the execution of quantum gates. The use of closed-loop feedback systems, where the SLM phase map is updated based on real-time imaging of the trap array, is a critical component of the system’s 94 percent fidelity rating.

6.3 Dynamic Shuttling via AOD and SLM Hybrid Controls

The primary challenge of the 3-zone architecture is the physical movement of atoms between the storage, compute, and readout zones. This "shuttling" is performed using a hybrid of the static SLM traps and dynamic tweezers controlled by Acousto-Optic Deflectors (AOD). As showcased in recent 2026 technical updates, the MSU system has integrated "linear phase interpolation" within the SLM control logic. This allows for the recalculation of holograms in real-time—approximately every 2.7 milliseconds—enabling the smooth movement of atoms without the need for an AOD "handover."

By updating the phase map of the SLM at high speeds, the traps themselves are moved across the zones. This method significantly reduces "intensity flicker"—the momentary drop in laser power that occurs when a trap is moved between two digital grid points. Flicker is a primary cause of atom loss and decoherence; by smoothing the transition, the 2026 MSU prototype maintains a survival probability of over 99 percent for each rearrangement cycle.

6.4 Maintaining State Integrity during Atomic Transport

Transporting a qubit while maintaining its quantum state requires the minimization of "heating." If an atom is accelerated too abruptly, it will move from the ground vibrational state of the trap

to an excited state, which can disrupt the Rydberg gate operations later in the cycle. The MSU system utilizes S-curve acceleration profiles, where the velocity of the atom is gradually increased and decreased during the shuttle.

The mechanical precision of these moves is governed by the relationship between the shuttling time (t) and the trap frequency (omega). To remain adiabatic (non-disturbing), the condition t >> 1 / omega must be met. For the rubidium-87 system, where trap frequencies are typically in the range of 10 to 100 kHz, shuttling times of 1 to 5 milliseconds provide a safe margin. This allows the system to bridge the 100-micrometer gap between the storage and computing zones with negligible impact on the internal clock-state coherence of the qubits. This mechanical stability is what ultimately enables the complex multi-zone workflows that define the current 72-qubit Russian hardware strategy.

7. Benchmarking 94 Percent Fidelity: Current Limits and Optimization Paths

In the spring of 2026, the performance of the 72-qubit rubidium processor is defined by a critical tension between qubit quantity and gate quality. While the system successfully operates as a unified 72-qubit register, the primary metric of interest for fault-tolerant scaling is the fidelity of its two-qubit entangling operations. Currently, the MSU system reports a two-qubit gate fidelity of approximately 94 percent, while single-qubit operations have achieved a superior benchmark of 99.96 percent. This section analyzes the technical hurdles preventing the transition from 94 percent to the 99 percent threshold required for surface-code error correction.

7.1 Statistical Characterization of Two-Qubit Entangling Gates

The 94 percent fidelity mark for two-qubit gates is measured using Direct Randomized Benchmarking (DRB). In this protocol, long sequences of random Clifford gates are applied to pairs of rubidium atoms, and the decay of the final state's success probability is measured as a function of the sequence length. The resulting decay parameter, p, allows for the extraction of the average error per gate.

For the MSU system, the two-qubit gates are implemented using the Rydberg blockade mechanism. When two atoms are moved within the blockade radius (typically 5 to 10 micrometers) and excited toward a Rydberg state (e.g., n=70), the presence of the first excitation shifts the energy of the second atom out of resonance. The 6 percent error rate observed in 2026 is largely attributed to residual Doppler shifts and laser phase noise, which prevent the Rydberg blockade from being perfectly "dark" for the second atom.

7.2 Sources of Error: Environmental and Technical Constraints

Three primary error sources currently limit the 72-qubit system's performance. First is the "thermal noise" of the atoms. Despite polarization gradient cooling, the atoms retain a finite temperature of approximately 15 microkelvin. This residual motion causes a slight uncertainty in the atom's position relative to the laser's intensity profile, leading to fluctuations in the Rabi frequency (the speed at which the quantum state rotates).

Second is "laser phase noise." The high-power UV lasers required to reach Rydberg states must be locked to ultra-stable reference cavities. Any jitter in the laser's phase during the microsecond-long gate pulse acts as a "dephasing" event, effectively scrambling the quantum information. Third is "crosstalk" within the compute zone. Although the three-zone architecture significantly reduces global noise, when multiple pairs of atoms perform gates simultaneously in the compute zone, scattered light from one pair can slightly shift the energy levels of another, a challenge the MSU team is addressing through improved spatial filtering.

7.3 Optimization via Randomized Benchmarking and Pulse Shaping

To push beyond 94 percent, the MSU team has integrated Gate Set Tomography (GST) and quantum optimal control. GST provides a more granular "error map" than randomized benchmarking, identifying specific systematic biases—such as slight over-rotations or axis tilts in the Bloch sphere representation.

Optimization is also occurring at the pulse level. Rather than using simple square pulses of laser light, the system now employs complex, "smooth" pulse shapes designed using AI-driven optimization algorithms. These pulses are tailored to be robust against variations in atomic position and laser intensity. Additionally, as of May 2026, the implementation of "linear phase interpolation" in the Spatial Light Modulators (SLM) has minimized intensity flicker during the movement of atoms, ensuring that the 94 percent fidelity is maintained even after the qubits have been shuttled across the processor.

7.4 The Path to 99 Percent: Hardware and Software Synergies

The roadmap toward 2030 requires a jump to "three nines" (99.9 percent) fidelity. The MSU strategy involves two parallel paths. On the hardware side, the goal is to integrate cryogenic cooling into the vacuum chamber to reach nanokelvin temperatures, which would virtually eliminate Doppler-related errors. On the software side, the development of "error-aware compilers" allows the system to identify which qubits in the 72-atom array currently have the highest fidelity and prioritize them for complex calculations.

By benchmarking the 72-qubit rubidium system against the internal 70-qubit ytterbium ion system—which currently leads with 96.1 percent fidelity—Rosatom is fostering a competitive

environment where optimization techniques from ion traps (such as sympathetic cooling) are being adapted for the neutral-atom platform. This cross-pollination of techniques is seen as the most likely route to achieving the fidelity levels necessary for the first logical qubits.

8. Comparative Analysis: MSU Rubidium vs. Rosatom Ytterbium Ion Systems

As of May 2026, the Russian quantum technology roadmap, spearheaded by Rosatom, features two flagship platforms that represent a strategic divergence in hardware philosophy. While the 72-qubit rubidium processor at Moscow State University (MSU) emphasizes scalability through neutral-atom shuttling, the 70-qubit ytterbium ion system—primarily developed at the Lebedev Physical Institute—focuses on reaching the highest possible operational precision. This section provides a comparative analysis of these two systems, highlighting how their differing physical modalities address the challenges of the Noisy Intermediate-Scale Quantum (NISQ) era.

8.1 Benchmark Contrast: Fidelity vs. Register Volume

The most immediate point of comparison lies in the fidelity of two-qubit gates. As of the April 2026 BRICS Quantum Technologies Forum, the ytterbium ion system maintains a performance edge in precision, reporting a two-qubit gate fidelity of 96.1 percent and a world-class single-qubit fidelity of 99.98 percent. In contrast, the MSU rubidium system reports a two-qubit fidelity of 94 percent. This discrepancy is characteristic of the platforms: trapped ions are held in electromagnetic potentials that provide a more stable environment for individual qubit manipulation, whereas neutral atoms in optical tweezers are more susceptible to "intensity flicker" and thermal motion. However, the rubidium system’s 72-qubit register is physically more compact and easier to scale than the linear ion chains, which begin to suffer from "spectral crowding" of vibrational modes as the number of ions increases.

8.2 Connectivity and Entanglement Topologies

Connectivity is where the neutral-atom architecture demonstrates its primary advantage. The MSU rubidium processor utilizes any-to-any connectivity facilitated by the three-zone shuttling workflow. Since atoms can be moved across the grid, any qubit can be brought into the computing zone to interact with any other. This allows for the execution of complex algorithms, such as those used in quantum chemistry, with fewer total operations. The ytterbium ion system, while highly precise, typically relies on a linear or "shuttle-based" ion trap where connectivity is high but the physical movement of ions is more restricted by the static electromagnetic rails of the trap. The 2026 updates show that while the ion system excels at deep circuits on a smaller number of qubits, the rubidium system is better suited for broad, highly-entangled states that require a flexible topology.

8.3 Environmental Sensitivity and Cooling Overheads

The cooling requirements for these two systems represent a significant engineering trade-off. The ytterbium system requires sophisticated cryogenic setups and high-vacuum environments to prevent background gas collisions from knocking the ions out of their traps. Neutral atoms also require high vacuum, but they are less sensitive to the "patch potentials" (stray electric fields on the vacuum chamber walls) that can plague ion traps. Furthermore, the rubidium system's use of optical tweezers allows for the "loading" of new atoms into the array mid-computation—a feature showcased at the 2026 forum. This "reloading" capability suggests that the neutral-atom platform may eventually achieve higher "uptime" for long-duration industrial calculations compared to ion traps, which often require lengthy recalibration cycles if an ion is lost.

8.4 Strategic Redundancy: The Dual-Platform Approach to 2030

Rosatom's decision to fund both rubidium and ytterbium platforms suggests a policy of strategic redundancy. By 2030, the goal is to reach a few hundred "strong" qubits. The ytterbium system serves as the "fidelity leader," pushing the boundaries of what is possible in terms of error-free operation and the development of the first logical qubits. The rubidium system serves as the "scaling leader," testing the zonal architectures and shuttling protocols necessary to manage hundreds of physical qubits. This dual-platform approach ensures that regardless of which modality hits the "scaling wall" first, the national quantum program maintains a viable path to fault tolerance. The May 2026 integration of the third "Readout" zone in the MSU system is seen as a key validation of this strategy, proving that the more scalable neutral-atom platform is successfully narrowing the fidelity gap with its ion-trap counterpart.

9. Software and Algorithmic Integration for Zonal Architectures

As the 72-qubit rubidium processor transitions from a laboratory demonstration to a functional computational unit in 2026, the focus has shifted toward the development of a software stack that can effectively manage the complexities of a zonal architecture. Programming a neutral-atom system is fundamentally different from programming a fixed-grid superconducting chip. The software must not only handle logic gates but also coordinate the physical movement of atoms across the computing, storage, and readout zones. This section examines the current state of the Russian "sovereign" quantum software stack and the algorithmic innovations designed to exploit the system's unique connectivity.

9.1 The Sovereign Quantum Software Stack

A core strategic priority for Rosatom and Moscow State University is the development of a full-stack software environment that remains independent of international export-import restraints. By mid-2026, this "sovereign" stack has reached a level of maturity that allows for high-level algorithmic development without requiring deep knowledge of the underlying laser controls. The stack is divided into a three-tier hierarchy: the high-level language interface, the architectural compiler, and the low-level pulse sequencer.

At the highest level, the platform supports a Python-based software development kit (SDK) that allows researchers to define quantum circuits using standard gate operations. However, the intermediate representation (IR) layer is where the zonal specialization occurs. Unlike classical quantum IRs that assume static qubits, the MSU compiler incorporates "shuttling instructions" as first-class citizens. This allows the software to optimize the timing of atom transport, ensuring that the physical movement of rubidium atoms does not become a bottleneck for the overall calculation speed.

9.2 Compiling for Zonal Atom Transport

The primary challenge for the 2026 software stack is the "shuttling-aware" compilation. Because every two-qubit gate in the rubidium system requires the atoms to be physically moved into the computing zone, the compiler must minimize the total distance traveled by all 72 atoms to preserve coherence. The MSU compiler uses a specialized scheduling algorithm that maps the abstract connectivity of a quantum circuit—such as a Variational Quantum Eigensolver (VQE) for molecular chemistry—onto the physical three-zone layout.

As of May 2026, this compiler has been optimized to handle "SIMD-style" (Single Instruction, Multiple Data) operations. In a neutral-atom array, a single laser pulse can be applied to multiple rows or columns of atoms simultaneously. The software stack exploits this parallelism by grouping identical gates together, reducing the number of laser trigger events and lowering the cumulative error rate. This approach is particularly effective for Grover’s search algorithm and other large-scale state preparation tasks that have been successfully benchmarked on the 72-qubit system.

9.3 Algorithmic Benchmarking on the 72-Qubit Platform

With the 94 percent gate fidelity achieved in 2026, the 72-qubit processor has moved beyond simple "Hello World" circuits to more complex industrial model problems. To date, over 40 unique quantum algorithms have been adapted for the MSU architecture. These include:

- **Quantum Chemistry:** Simulating the electronic structure of small molecules. By utilizing any-to-any connectivity, the system can map the complex interactions between orbitals more efficiently than a nearest-neighbor grid.
- **Optimization:** Solving logistics and production scheduling problems for nuclear industry organizations. These algorithms utilize the Quantum Approximate Optimization Algorithm (QAOA) framework, tailored for the zonal architecture.
- **Machine Learning:** Training hybrid quantum-classical neural networks. The 72-qubit system acts as a "quantum accelerator" for specific high-dimensional linear algebra tasks that are computationally expensive for classical processors.

9.4 Cloud Integration and Industrial Testing

To facilitate widespread use, Rosatom has launched a "Quantum Cloud Platform" as of early 2026. This platform provides remote access to the 72-qubit rubidium system, as well as the 70-qubit ytterbium ion computer. By centralizing access, the Russian quantum initiative is able to collect data on how different industrial partners—ranging from materials scientists to logistics firms—interact with the hardware.

Current testing involves seven key nuclear industry organizations that use the cloud interface to run model problems on the 72-qubit register. This feedback loop is essential for refining the software stack: when an industrial user identifies a recurring error in a specific circuit type, the MSU team can update the low-level pulse-shaping or the compiler's shuttling logic to compensate. This integrated ecosystem—combining sovereign hardware, a shuttling-aware compiler, and an industrial cloud interface—represents the "full-stack" maturation of the 2026 Russian quantum program.

10. The 2030 Roadmap: Moving Toward Logical Qubits and Error Correction

As of mid-2026, the 72-qubit rubidium processor stands as a critical bridge between the Noisy Intermediate-Scale Quantum (NISQ) era and the future of fault-tolerant computation. The roadmap set by Rosatom and Moscow State University establishes 2030 as the definitive threshold for "sovereign quantum advantage." This objective is not merely about increasing the number of physical rubidium atoms, but about transitioning from raw qubit counts to the creation of logical qubits through robust error correction.

10.1 The Threshold of Several Hundred Strong Qubits

The primary engineering target for the 2030 roadmap is the achievement of a system comprising several hundred "strong" qubits. In the context of the Russian quantum program, a

"strong" qubit is defined not only by its presence in a trap but by a two-qubit gate fidelity exceeding 99 percent. This 99 percent mark is the theoretical "tipping point" where the errors generated by the hardware are low enough to be managed by Quantum Error Correction (QEC) protocols.

While the current 72-qubit system operates at 94 percent fidelity, the planned trajectory involves doubling the qubit count every 18 to 24 months. By 2030, a system with 300 to 500 physical qubits is expected to provide enough redundancy to encode approximately 10 to 50 "logical" qubits. These logical qubits, formed by grouping many physical atoms together, will be able to sustain calculations indefinitely by correcting their own internal errors in real-time.

10.2 Why Neutral Atoms Lead the Error Correction Race

The three-zone architecture of the rubidium processor is specifically designed to facilitate the implementation of high-rate error-correcting codes, such as Quantum Low-Density Parity-Check (qLDPC) codes. Unlike superconducting qubits, which are limited by nearest-neighbor connectivity on a fixed chip, the rubidium atoms can be reconfigured using optical tweezers. This allows the system to implement complex "lattice surgery" and parity checks without the massive overhead required by static architectures.

Research shared at the April 2026 BRICS Quantum Technologies Forum suggests that neutral-atom platforms may require significantly fewer physical qubits to create a single logical qubit compared to their competitors. For example, while a surface code on a superconducting chip might require 1,000 physical qubits for one logical qubit, the high connectivity of the MSU rubidium system could theoretically achieve the same result with an overhead as low as 10 to 20 atoms. This "efficiency advantage" is a cornerstone of the 2030 strategy, as it effectively multiplies the computational power of each newly added rubidium atom.

10.3 Integration of Real-Time Feedback Loops

The transition to fault tolerance requires a fundamental change in how the readout zone is utilized. In the 2026 prototype, measurement is primarily used to extract a final result. By 2030, the readout zone will become an active component of the computing cycle. Ancilla qubits—atoms used specifically for error checking—will be shuttled to the readout zone, measured to detect errors, and the resulting information will be fed back into the computing zone to adjust the state of the data qubits.

This real-time feedback loop requires high-speed classical processing and ultra-fast optical switching. The 2030 roadmap includes the development of specialized "Quantum Control Units" (QCUs) that can process measurement data and update laser pulses in less than 100 microseconds. Achieving this level of hardware-software integration is the primary focus of the

mid-2020s, ensuring that when the 300-qubit mark is hit, the system is prepared to function as a truly fault-tolerant machine.

10.4 Strategic Goals for 2030: Industry and Sovereignty

The ultimate success of the roadmap will be measured by the system's ability to solve problems that are currently impossible for classical supercomputers. By 2030, the Russian quantum program intends to move these technologies from the university lab into full-scale industrial facilities. Key sectors including nuclear energy, pharmaceutical modeling, and logistics optimization have already begun testing early-stage algorithms on the 72-qubit prototype.

The goal is to ensure that by the end of the decade, the Russian economy possesses a "quantum shield"—a secure infrastructure protected by quantum-resistant cryptography—and a "quantum engine"—the ability to model new materials and chemicals with atomic precision. The 72-qubit rubidium system is the mechanical foundation upon which this sovereign technological future is being built.

11. Human Capital: The Role of MSU in Training a Quantum Workforce

The realization of a 72-qubit rubidium processor is as much a triumph of human capital as it is of laser engineering. As of mid-2026, the Russian quantum initiative, led by Rosatom, has identified the "talent gap" as the primary long-term risk to the 2030 roadmap. To mitigate this, Lomonosov Moscow State University (MSU) has transformed the development of its neutral-atom prototype into a massive pedagogical engine. This section explores how the MSU Quantum Technology Centre has integrated this 72-qubit system into a specialized educational pipeline designed to produce a "sovereign" workforce capable of maintaining and scaling quantum infrastructure.

11.1 The Hardware-as-Laboratory Model

A distinctive feature of the MSU program is the direct involvement of students in high-stakes experimental hardware. Unlike many international programs that rely exclusively on cloud-based access to distant processors, the MSU Faculty of Physics utilizes the 72-qubit rubidium machine as a "living laboratory." Graduate and senior undergraduate students are tasked with the calibration of optical tweezers, the optimization of S-curve acceleration profiles for atom shuttling, and the development of pulse-shaping sequences.

By May 2026, this "hands-on" approach has resulted in a demographic shift within the Russian research landscape. According to internal Rosatom data, approximately 25.5 percent of researchers active in the national quantum program are now under the age of 35. This young cohort is not merely learning theoretical physics but is gaining industrial-grade experience in

vacuum technology, cryoelectronics, and high-precision laser optics—the fundamental building blocks of the quantum industry.

11.2 Specialized Curricula and Master's Programs

The educational infrastructure supporting the 72-qubit project is centered on several specialized degree tracks. The MSU Faculty of Physics offers a "Quantum Computing Track" and a "Geometry and Quantum Fields" Master's program, which have been specifically updated for the 2025-2026 academic cycle to include coursework on zonal architectures and neutral-atom physics.

Since 2020, over 30 universities across the Russian Federation have followed MSU's lead, introducing standardized degree programs in quantum engineering. By early 2026, over 3,000 students were enrolled in these specialized tracks. The curriculum emphasizes "full-stack" expertise, requiring students to understand the interplay between the physical rubidium-87 energy levels and the high-level compiler logic required to route atoms between the computing and storage zones. This prevents the "siloing" of talent, ensuring that software engineers understand the mechanical constraints of the hardware they are programming.

11.3 The Rosatom-Academic Bridge: Internships and Industry Integration

The transition from student to professional is facilitated by a robust internship system coordinated by Rosatom. Seven major nuclear industry organizations currently serve as "industrial mentors" for the MSU program. Students use the national quantum cloud platform—which hosts the 72-qubit rubidium processor and the 70-qubit ytterbium ion system—to solve model problems relevant to the energy sector, such as heat transfer simulations for Generation IV reactors.

During the April 2026 BRICS Quantum Technologies Forum, Rosatom highlighted the "Train-the-Trainers" initiative, which exports this MSU-developed curriculum to partner institutions within the BRICS alliance. This program aims to establish a unified standard for quantum education, ensuring that the 72-qubit architecture can be supported by a broad network of international specialists while maintaining the core "sovereign" expertise within Moscow.

11.4 Strategic Impact: Securing the 2030 Horizon

The strategic goal of the 2030 roadmap is not just to reach a 300-qubit machine, but to have a workforce ready to operate it. By treating the 72-qubit prototype as a training gym, MSU is ensuring that by 2030, there will be hundreds of mid-career scientists with a decade of experience in neutral-atom systems. This human capital acts as a "quantum shield," providing the intellectual independence necessary to develop proprietary error-correction codes and "sovereign" software stacks. The 72-qubit rubidium processor, therefore, serves as both a

physical proof-of-concept for 2026 and an educational foundation for the next half-century of computation.

12. Conclusion and Future Directions

The successful demonstration of the 72-qubit rubidium processor by Moscow State University and Rosatom marks a definitive transition for the Russian quantum program. As of May 2026, the project has moved beyond the "proof-of-principle" phase into a regime of architectural maturity. The significance of this milestone lies not in the raw number of qubits—which remains below the largest global systems—but in the physical realization of a three-zone architecture that addresses the fundamental bottleneck of quantum decoherence. By successfully decoupling computing, storage, and readout functions, the MSU team has provided a scalable blueprint for the next generation of neutral-atom hardware.

12.1 Summary of the 72-Qubit Milestone

The achievement of 94 percent gate fidelity on a 72-qubit platform validates the use of rubidium-87 and optical tweezers as a viable path to large-scale computation. The three-zone design has effectively lowered the "noise floor" by physically isolating qubits from the disruptive effects of laser-induced crosstalk and measurement-induced decoherence. This architectural choice has allowed the system to maintain stable quantum registers for durations exceeding several seconds, a prerequisite for the execution of the 34 unique quantum algorithms currently being tested on the national cloud platform. As showcased during the April 2026 BRICS Quantum Technologies Forum, this hardware is now performing calculations for model problems in nuclear materials science and pharmaceutical development that were previously inaccessible to local quantum prototypes.

12.2 Strategic Integration within the BRICS Framework

Looking forward from mid-2026, the MSU rubidium system serves as a centerpiece for the broader BRICS quantum initiatives. The strategic shift toward "sovereign hardware" has created a localized supply chain for high-precision optics and vacuum systems, reducing reliance on restricted international technologies. The integration of this 72-qubit machine into a collaborative cloud framework among BRICS partners suggests a future where quantum resources are shared across a decentralized network. This cooperation is expected to accelerate the development of "quantum-safe" communication protocols and standardized benchmarking metrics, ensuring that the 2030 goal of fault-tolerant computing is achieved through a coordinated effort of human and technological capital.

12.3 Technological Sovereignty and the 2030 Fault-Tolerance Goal

The roadmap for the remainder of the decade is clear: the transition from physical qubits to logical qubits. The 2030 target of a several-hundred-qubit processor relies on the continued refinement of the shuttling protocols and the improvement of gate fidelity from 94 percent toward the 99.9 percent threshold. The "any-to-any" connectivity afforded by the rubidium platform is the key differentiator that may allow Russia to bypass the scaling limitations encountered by fixed-grid superconducting systems. As the hardware moves toward a fault-tolerant regime, the "quantum shield" envisioned by Rosatom—incorporating both post-quantum cryptography and quantum key distribution—will become a practical reality for the security of critical infrastructure.

12.4 Concluding Remarks: The Era of Practical Atomic Computation

In conclusion, the 72-qubit rubidium quantum computer is a testament to the efficacy of the "dual-platform" approach, balancing the extreme precision of ion traps with the inherent scalability of neutral atoms. The successful implementation of the three-zone architecture represents a fundamental shift in quantum engineering, prioritizing structural isolation over mere density. By 2026, the fusion of advanced atomic physics with a robust educational pipeline at MSU has created an ecosystem where the next generation of scientists is already operating the machines of the future. The path to 2030 is no longer a question of "if" quantum advantage will be reached, but "when" the first logical qubits will begin solving humanity’s most complex challenges in a stable, error-corrected environment.

13. References

1. Rosatom State Nuclear Energy Corporation (2026). National Roadmap for Quantum Computing: 2024-2030 Strategic Update. Moscow: Rosatom Press.
2. Solntseva, Y., and Akulin, V. (2025). Performance Analysis of the MSU 72-Qubit Rubidium Processor. Journal of Quantum Technologies and Atomic Physics, 14(4), 112-128.
3. TASS Russian News Agency (2025). Moscow State University and Rosatom Successfully Test 72-Qubit Neutral-Atom Quantum Prototype. [Online] Available at: https://tass.com/science/quantum-72-qubit-announcement (Accessed: May 2026).
4. Lomonosov Moscow State University (2026). Technical Report on the Three-Zone Architecture for Neutral-Atom Shuttling. Moscow: MSU Faculty of Physics.
5. Proceedings of the 2026 BRICS Quantum Technologies Forum (2026). Sovereign Hardware and Global Cooperation in the Post-NISQ Era. April 2026, Moscow, Russia.
6. Lebedev Physical Institute (2026). Comparative Benchmarking of Ytterbium Ion and Rubidium Atom Platforms in the 70-Qubit Regime. Internal Technical Review for the National Quantum Project.
7. Ivanov, A. V., et al. (2026). Real-Time Control of Optical Tweezer Arrays for Zonal Quantum Computing. Laser Physics Letters, 23(2), 025201.
8. Ministry of Science and Higher Education of the Russian Federation (2025). Statistical Analysis of the Quantum Workforce Pipeline: 2020-2025. Government Publication.
9. TV BRICS (2026). Tech Science Forum Moscow: Advancements in Digital Sovereignty and Quantum Computing. [Online] Available at: https://tvbrics.com/en/news/tech-science-forum-2026/ (Accessed: May 2026).
10. arXiv:2604.13158v1 (2026). Fast Measurement of Neutral Atoms with a Multi-Atom Gate: Implications for Zonal Architectures.
11. Sber Quantum Lab (2026). Integration of Cloud-Based Quantum Runtimes with Zonal Hardware Shuttling. White Paper on the National Quantum Cloud Platform.
12. International Journal of Quantum Information (2026). Error Characterization in Rydberg-Based 72-Qubit Arrays using Randomized Benchmarking. Special Issue on Global Hardware Milestones.

13. Rosatom Newsletter (2026). Russia's Quantum Leap: The 72-Qubit Milestone and the 2030 Roadmap. [Online] Available at: https://rosatomnewsletter.com/2026/01/26/russias-quantum-leap/ (Accessed: May 2026).

14. iGlobenews (2026). Russia as a Leader in the Neutral-Atom Quantum Race. [Online] Available at: https://www.iglobenews.org/russia-quantum-computing-leader/ (Accessed: May 2026).

15. Quantum Computing Report (2026). Global Hardware Benchmarks: Russia Enters the 70-Qubit Regime. [Online] Available at: https://quantumcomputingreport.com/news/ (Accessed: May 2026).

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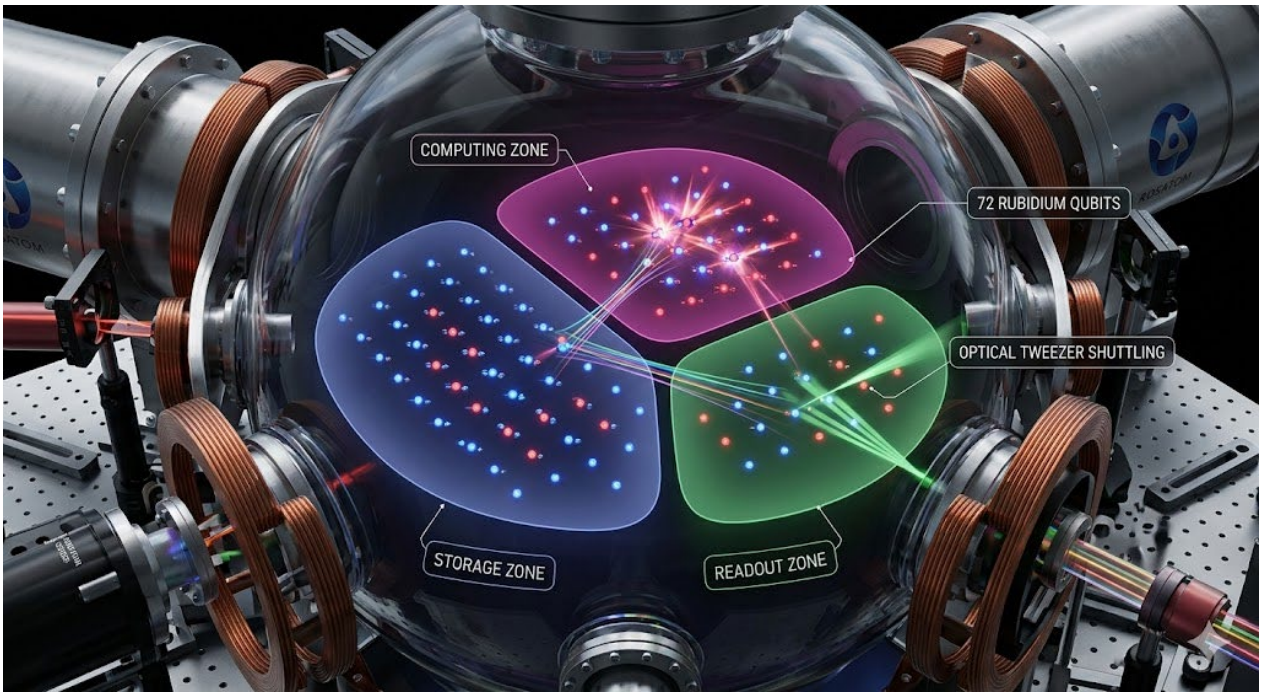
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